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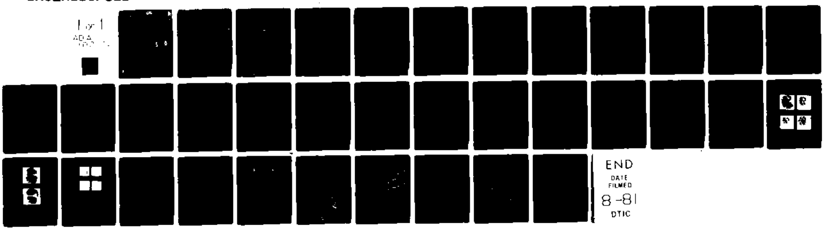

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The broad purpose of this research has been to investigate the dynamics of flowing plasmas. Attention has been given to the processes which transfer momentum between interacting ion species in counterstreaming plasms produced by laser irradiation of a solid target. This investigation has evolved from an examination of collisional interactions with conventional diagnostics to an extensive study of collisionless momentum transfer in magnetic fields using a broad spectrum of diagnostics, including resonant optical techniques. This final report focuses on the concluding phase of the research performed under

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FINAL REPORT

to the

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

on

AFOSR [redacted] 76-2991

EXPERIMENTAL STUDIES OF ION CHARGE AND ION FLUX IN STREAMING PLASMAS

For the Period

October 1, 1979 - December 31, 1980

Principal Investigators: David W. Koopman
Joseph Silverman

Institute for Physical Science and Technology
University of Maryland, College Park, MD 20742

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I. INTRODUCTION

This final report focuses on the concluding phase of the research performed under AFOSR [redacted]-76-2991, especially during the twelve month period from October 1, 1979 to December 30, 1980. The Principal Investigator, D. W. Koopman, died in December, 1979, at which time Dr. J. Silverman, the Director of the Institute for Physical Science and Technology, assumed the responsibilities for management of the grant. Following Dr. Koopman's death, the research was performed by Dr. C. R. Parsons, Research Associate and G. Jellison, Research Assistant and Ph.D. candidate.

The broad purpose of this research has been to investigate the dynamics of flowing plasmas. Attention has been given to the processes which transfer momentum between interacting ion species in counterstreaming plasmas produced by laser irradiation of a solid target. This investigation has evolved from an examination of collisional interactions with conventional diagnostics to an extensive study of collisionless momentum transfer in magnetic fields using a broad spectrum of diagnostics, including resonant optical techniques.

Funding for this experiment was extended through December, 1980 and then terminated. The final phase of this study will generate several additional papers detailing specific results; G. Jellison's doctoral dissertation, to be completed in early 1981, will provide a comprehensive review of the project and its ultimate conclusions.

This Final Report summarizes our present understanding of the phenomena observed in the experiment. The research facilities are described in Section II. Section III reviews the experimental results. These include the construction

and application of a novel resonant optical diagnostic system, observations of magnetized plasma flow into vacuum, and studies of collisionless plasma coupling to photoionized background gas.

II. EXPERIMENTAL FACILITIES

The investigation in its final stages was performed in an epoxy-glass vacuum chamber three feet long and fifteen inches in diameter, (Fig. 1). Ports arranged around the middle of the cylinder accommodate diagnostic probes and the end plates have large windows eight inches high extending across the diameter of the chamber, allowing the entire interior of the chamber to be viewed and to admit light for optical diagnostics. A four-inch diffusion pump achieves a base pressure of 10^{-5} torr, adequate for collisionless interaction studies.

A pair of water cooled electromagnet coils is installed around the chamber. These produce a magnetic field variable from 250 to 2000 gauss, and uniform over a volume of 5000 cm^3. The field is transverse to the plasma flow direction.

An expanding plasma is produced when a 5J, 100 nsec pulse from a TEA CO_2 laser is directed across the diameter of the cylinder and is focused onto the solid target just inside the chamber wall.

The strong ultraviolet emission that accompanies plasma production will ionize a portion of any background gas that may be introduced, providing a stationary plasma through which the expanding plasma must stream.

Langmuir probes and optical diagnostics have provided most of the data during the concluding stages of this investigation. Optical diagnostics are performed with a 2 megawatt, 20 nsec pulsed dye laser, tunable from 4500 to 4600 Å, with a spectral width of 0.3 Å. The lasing dye is pumped by frequency

doubled light from a 5J, 20 nsec Q-switched ruby laser. When the dye laser is tuned to the BaII ion resonance line at 4554.03 Å, sensitivity to laser-produced barium plasma is enhanced by several orders of magnitude. As described in the next section, this diagnostic allows the measurement of plasma densities too low to be studied by conventional optical diagnostics.

III. EXPERIMENTAL RESULTS

A. Development of Resonant Optical Diagnostics

During the last several years, we have been investigating the application of resonant optical diagnostics to low-density laser-produced plasma flows. Dye laser light tuned to the BaII $6p^2P_{3/2}$ - $6s^2S_{1/2}$ transition at 4554.03 Å interacts strongly with the singly ionized component of the plasma, and allows resonant holographic interferometry, resonant scattering, and resonant shadowgraph and schlieren photography to be done in our experiment.

Holographic interferometry was studied intensively during the earlier stages of this project, and the results were reported in a published paper,

> "Turbulent Interaction Fronts in Counterstreaming Laser-Produced Plasma Studies", by D. W. Koopman, H.-J. Siebeneck, and G. Jellison, Phys. Fluids 22, 526-533 (1974).

It was found that this technique is useful for studying the strong collisional snowplow interaction between an unmagnetized barium plasma and a high-pressure (~ 1 torr) deuterium background.

The technique of resonant scattering was investigated in the latter stages of the project. We were thereby able to corroborate the results of our other diagnostic techniques. It was found, however, that optical thickness problems prohibited the use of resonant scattering for densities above 10^{12} cm^{-3}.

These results were reported in a poster session

> "Investigation of the Dynamics of Laser-Produced Plasma by Resonant Scattering", by C. R. Parsons, G. Jellison, and D. W. Koopman, Bull. Am. Phys. Soc. 24, 1025 (1979) at the 1979 meeting of the Plasma Physics Division of the American Physical Society.

We have found that resonant schlieren and shadowgraph photography[1] are the simplest and most sensitive of our optical techniques. We have therefore used these methods extensively, in both the earlier collision-dominated studies, and in the more recent stages of the project. The information thus obtained about magnetized plasma flow is discussed in the next section.

B. Studies of Magnetized Flow into Vacuum

We have undertaken a detailed study of the phenomena which accompany vacuum expansion of the barium plasma. Because the field is strong, for radii $\gtrsim 4$ cm, the magnetic pressure $B^2/8\pi$ exceeds the plasma kinetic pressure $nm_i U^2$, where n is number density, m_i is ion mass, and U is directed flow velocity. Thus significant perturbation, and perhaps partial confinement, of the plasma by the field might be expected.

We find that the barium plasma flows with nearly constant velocity across the field. However, visual inspection shows that the plasma is vertically compressed into a narrow, collimated beam that follows a nearly straight trajectory across the vacuum chamber. It is clear that the field is responsible for this significant deviation from the quasispherical expansion which characterizes unmagnetized flow.

The dynamics of the magnetized flow can be conveniently studied by our optical diagnostic system. The results are included in a manuscript

> "Resonant Shadowgraph and Schlieren Studies of Magnetized Laser-Produced Plasmas", by G. Jellison and C. R. Parsons,

which has been submitted to Physics of Fluids and which is included in this report as an Appendix. A significant feature of this study is the discovery of separate fast and slow plasma components with well-defined boundaries. The fast component is seen in the shadowgraph pictures to have a wedge shape, with a narrow beam extending forward from the vertex. The slow component displays internal striations in shadowgraph and schlieren pictures. The striations are evidently made visible by the refractive effects of strong density gradients, indicating the presence of shock waves in this portion of the plasma.

Electric and magnetic probe measurements confirm the above observations, and suggest a model for plasma propagation across the field. The mechanism usually cited as responsible for the plasma motion across the field in experiments similar to this one is $\vec{E} \times \vec{B}$ drift.[2] Potentials of ~ 100 V, roughly what is needed to produce the observed drift velocity, have been observed in this work. It has been observed in plasma gun experiments that a conductor in contact with the plasma can drain the polarization charge layers and inhibit plasma flow;[3] theory suggests that the stopping distance should be proportional to the ion Larmor radius.[4] A copper plate in contact with the flowing plasma in our experiment can indeed disrupt the narrow plasma beam and stop the plasma within 20 cm. As expected, this effect is more pronounced for lighter target materials, such as carbon and aluminum, than for heavy targets like copper and barium, because of the ion Larmor radius dependence. These observations confirm that large-scale polarization E-fields are indeed necessary for laser-plasma flow across the field, and offer the first experimental test of the Larmor radius dependence of the stopping distance.

C. Studies of Magnetized Flow into Background Gas

1. Theoretical Considerations

As we have already noted, the addition of a low-density gas to the vacuum chamber provides an initially stationary background plasma, with which the barium plasma may interact. Such interactions can be divided into two classes. Collisional coupling can be produced by Coulomb interactions between charged species, and a series of publications has detailed how momentum transfer and shock-like fronts can be produced by collisional processes.[5-7] In situations where the collisional mean free path is larger than experimental dimensions, collisional coupling may be negligible, and any significant interactions which occur must be based on the collisionless phenomena which arise from the ability of the plasma to carry waves and turbulent electric fields which may deflect and scatter particles as would collisions. Preliminary evidence for collisionless momentum transfer between counterstreaming plasmas was previously reported;[8] the present study has produced new information about the instabilities responsible for the coupling, and the dynamics of the coupling process.

The theoretical treatment of collisionless coupling is based on distribution functions of the type shown in Fig. 2; our experimental situation is well described by distributions of this type. The B-field is assumed to be transverse to the flow.

Magnetized counterstreaming plasmas have received considerable theoretical attention during the past ten years.[9-12] These studies have shown that there are two instabilities important for our experimental situation. The first of these is the direct ion-ion instability, the conditions for which are

(1): $$\frac{U}{V_i} \geq 4\alpha^{-1/3} ,$$

where V_i is the ion thermal speed and where $\alpha = \frac{n_1 Z_1^2 m_2}{n_2 Z_2^2 m_1}$, with n and m referring to the ions and the subscripts 1 and 2 referring to the background and flowing plasma components such that $\alpha \leq 1$, and

(2): $$U^2 \leq 1.5 \left(\frac{n_2}{ne}\right) Z_2 (1+\alpha^{1/3})^3 V_A^{\,2} (1+\beta_e)$$

where $V_A^2 = B^2/4\pi n_2 m_2$ and $\beta_e = 8\pi n e T_e/B^2$. The second important instability is the modified two-stream instability, with the conditions

(1): $$U > 2\,V_i \quad \text{and}$$

(2): $$\frac{U_{ie}}{V_A} < \frac{n_i Z_i}{ne} \sqrt{1+\beta_e} \times \left[1 + \frac{H}{1+(1+\Omega_e^2/\omega_e^2)^{1/2}(1+\beta_e)^{1/2}}\right] .$$

where U_{ie} is the relative electron-ion speed, $\Omega_e = eB/m_e c$, $\omega_e = (4\pi n_e\, e^2/m_e)^{1/2}$, and $H = \frac{\omega_e}{\omega_i}\,\theta$, where θ is the angle of propagation of the unstable waves, relative to $\vec{B}$.

By inserting our experimental parameters into the preceding equations, we can show that both of the above instabilities can occur in our experiment. When the instability criteria are satisfied, the instabilities extract kinetic energy from the counterstreaming plasmas and convert it to particle thermal energy. Thus, deceleration of the flowing plasma and heating of either electrons or ions are taken as evidence of the instabilities.

2. Experimental Results

Background gas pressure of about 1 micron should provide little collisional deceleration of the barium plasma, because the mean free path for multi-Coulomb collisions

$$L = \frac{m_1 m_2/(m_1+m_2)^2 U^4}{4\pi Z_1^2 Z_2^2 ne^4 \ell n\Lambda}$$

is larger than experimental dimensions. Experimentally, we indeed find that thereis little collisional coupling to a xenon background of 1 micron, in the unmagnetized case.

When a magnetic field is added, however, the dynamics of the flowing plasma changes noticeably. Figure 3 presents BaII density vs. time profiles as deduced from resonant scattering measurements. We see that addition of xenon produces an initial increase in BaII density, probably by a charge exchange process. More importantly, the main body of the plasma is seen to be decelerated by coupling to the background gas.

Langmuir probe measurements and photomultiplier observations of spontaneous emission at 4554.03 Å also show this delay in arrival time. We have therefore relied heavily upon these diagnostics, because unlike scattering they do not require the recording of multiple shots for a profile of density vs. time.

We find that the coupling begins when the B-field exceeds several hundred gauss. As the field is increased, the coupling strengthens. This is evidenced by a shorter interaction length, and a sharper front. In Fig. 4,

we show the reciprocal of the half-thickness of the plasma front (as deduced from observations of spontaneous luminosity) vs. field strength, for 1 micron background xenon pressure. We observe that the thickness of the front is inversely proportional to the field strength. This is understandable since the front thickness should be several times the coupling length, which, for the ion-ion instability, can be expressed as

$$L_s = 8\sqrt{2}\, U\left(\frac{m_i}{m_e}\right)^{\frac{1}{2}}\left(\frac{n_2}{n_1}\right) / \Omega_e \ ,$$

with a similar expression holding for the modified two-stream instability.[8] Evaluating the above expression, we find L_s = .5 - 1.0 cm for our experiment; this agrees well with the observed front thickness. We also note that the Ω_e term causes L_s to vary inversely with B, also in agreement with the data.

Further information about the instabilities can be obtained from the plasma luminosity. When no magnetic field is present, the electron temperature, as deduced from Langmuir probe measurements, is about 0.5 eV. Thus, the 4554.03 Å BaII transition, which has an excitation energy of 2.7 eV, will undergo little excitation, and spontaneous emission at this wavelength will be rather small. When the B-field, but no background gas, is present, the plasma luminosity increases by about one order of magnitude. Concurrently, the electron temperature rises, evidently because of the heating effects of field-induced micro-instabilities. The addition of low-pressure background gas further raises the luminosity by a factor of twenty. This indicates heating caused by conversion of counterstreaming kinetic energy to particle thermal energy. The effect is not collisional, because it does not occur in the absence of the B-field. Thus, the heating is further evidence of magnetically induced instabilities. It is likely that the modified two-stream instability is responsible for this effect, since theory predicts a heating rate from this

instability[11] of ~ 6 eV/μsec, and this is consistent with our measured temperature rise. The ion-ion instability produces little electron heating; thus these observations allow us to draw an important distinction between the two instability mechanisms for the first time.

The above measurements were reported in a poster session

> "Spontaneous Emission from Barium Resonance Lines in Magnetized Counterstreaming Plasmas", Bull. Am. Phys. Soc. 25, 1013 (1980),

at the November 1980 meeting of the Plasma Physics Division of the American Physical Society.

The existence of a strong interaction should result in a "snowplow" sweeping-up of the background plasma. This can be tested by studying the trajectory of the barium. Figure 5 shows the position vs. time of the plasma front, for two different background pressures. The trajectories conform to the predictions of the snowplow model, as deduced by the past[8] and present ongoing calculations.

Another model that has been applied to coupled plasmas in the past is provided by blast wave theory. For a partially photoionized background, the ionization fraction provided by a point source of UV radiation, such as in our experiment, will decrease as the inverse square of the radius; blast wave theory then predicts[13]

$$R \propto t^{2/3}$$

$$t \propto n^{1/2} ,$$

where n is background density. By making log-log plots of our data, we can test these predictions. As Fig. 6 and 7 show, the R-t dependence conforms

to blast-wave theory, but the t-n dependence is closer to $t \propto n^{2/5}$. We have noted deviations from the blast-wave model in earlier published studies,[14] and we are presently investigating the applicability of this model by comparing its predictions with those of the snowplow model. Results of this work and more extensive discussion of the topics described in this Report will appear in the PhD thesis of G. P. Jellison.

APPENDIX

"Resonant Shadowgraph and Schlieren Studies of Magnetized Laser-Produced Plasmas" by G. Jellison and C. R. Parsons. Manuscript submitted for publication to Physics of Fluids.

RESONANT SHADOWGRAPH AND SCHLIEREN STUDIES OF MAGNETIZED LASER-PRODUCED PLASMAS

G. Jellison and C.R. Parsons
Institute for Physical Science and Technology
University of Maryland
College Park, Maryland 20742

Resonant shadowgraph and schlieren techniques provide instantaneous photographs of a laser-produced barium plasma flowing across a transverse magnetic field. The field is seen to impose considerable structure upon the expanding plasma. The flow separates into several well-defined regions, according to velocity. The slow plasma component displays internal striations. These are interpreted as shock waves excited by plasma flow across the field.

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I. INTRODUCTION

Resonant optical diagnostics are useful in the study of low-density plasmas, provided a source of probing radiation exists at the resonance wavelength of one of the ion states present.[1-4] Resonant shadowgraph and schlieren techniques have recently been used to photograph the flow of unmagnetized laser-produced plasma into photoionized background gas.[5-6] We now report the application of these methods to laser-plasma flow across a magnetic field.

Barium was used as the target material because the Ba II $6p^2 P_{\frac{3}{2}} - 6s^2 S_{\frac{1}{2}}$ transition at 4554.03 Å is accessible to tunable dye laser light. This resonance line is used for measurement of plasma properties in two ways. First, the dye laser light can be absorbed by the plasma, giving attenuation of the light proportional to the density integrated along the probing beam. This effect is utilized in our shadowgraph studies. Second, by tuning the dye laser slightly off resonance, we can use the enhanced index of refraction adjacent to the resonance transition to visualize density gradients in the plasma.[5] This effect occurs in both the shadowgraph and the schlieren studies.

II. EXPERIMENTAL APPARATUS

The experiment, diagrammed in Fig. 1, is similar to the arrangement of Ref. 5. The plasma is formed by focusing a CO_2 TEA laser onto a solid barium target in a vacuum chamber (base pressure less than 10^{-5} torr). By varying the nitrogen content of the laser gas mixture, one can obtain either

a long 7J pulse, consisting of a 50 nsec initial spike followed by a 1 μsec tail, or a short 2J pulse, consisting of just the initial spike. The CO_2 laser wavelength is 10.6 μm.

A transverse magnetic field of 200 – 2000 G is provided by electromagnet coils. The field is uniform over the 10 cm scale of the present studies.

The tunable dye laser used for optical diagnostics is pumped by frequency-doubled Q-switched ruby laser light, and yields a 10 mJ 20 nsec pulse, with a spectral width of 0.25 Å. This beam is expanded, passed through the vacuum chamber, focused to a point, and allowed to re-expand and to illuminate the camera film. For the schlieren studies, a knife edge is placed at the laser focal spot, and the camera is focused onto the plasma region. For the shadowgraph work, the knife edge is omitted and the camera is deliberately not focused onto the plasma; this allows refractive effects to be seen in the shadowgraph pictures.[7]

The most important effect in the shadowgraphs, however, is simply absorption of the light by the 4554.03 Å Ba II transition. This absorption is proportional to $\int n_i d\ell$, where n_i is the singly ionized barium density, and the integral is taken along the dye laser beam. The sensitivity of the system is $\int n_i d\ell \approx 10^{13}/cm^2$.

In the schlieren configuration, the system responds to density gradients perpendicular to the laser beam. The system will record a change of image brightness if $xL(\partial\eta/\partial z)>d$, where x is the length of the nonuniformity along the probing beam, L is the plasma-to-knife edge distance, η is the index of refraction, d is the focal spot size, and z is perpendicular to both the beam and the knife edge. In our experiment, d=1mm, L=200cm, and $\eta=1+n_i\times$

Greek "eta"

Greek "lambda" $(1.56\times10^{-19})/(\lambda-\lambda_r)$, where λ is the laser wavelength and λ_r=4554.03 Å. If $x\approx10\ \partial z$ and $(\lambda-\lambda_r)\approx1$ Å, a density of approximately $3\times10^{14}/cm^3$ should give a visible signal, if fluctuations on the order of 100% exist. The sensitivity of this system is 100 to 1000 times greater than that of a nonresonant setup utilizing electron contributions to the index of refraction.

III. EXPERIMENTAL RESULTS

In Fig. 2, shadowgraphs of the barium plasma are shown. The target, a cylindrical rod 2 cm in diameter, is at the ~~left~~ right; the CO_2 laser light comes in from the ~~right~~ left, striking the flat face of the rod. The magnetic field goes into the page.

An adjustable delay generator triggers the dye laser, giving shadowgraphs of various stages of the plasma flow. One picture per plasma event can be taken.

In the shadowgraphs, absorption of the light renders the plasma visible as a dark cloud. As can be seen, the B-field compresses the front of the emerging plasma, giving well-defined edges. (In pictures taken with no field, a diffuse plasma cloud is seen, with no structure or sharp boundaries.) By 4 μsec after the CO_2 pulse, the leading edge of the plasma has assumed a wedge shape which persists at later times. By 6 μsec, the B-field has imposed considerable structure upon the expanding plasma. The leading edge has formed well-defined "wings" reminiscent of a supersonic bow shock. (It should be noted that no background gas is present in this work.) A slower, triangular plasma component can also be seen near the rod. At

8 μsec, a narrow beam of plasma can be seen extending from the vertex of the leading edge. By 10 μsec, the beam has become well-defined, and the plasma has assumed its final configuration, which persists for at least 30 μsec. The various plasma components travel across the magnetic field with constant velocity; the forward-pointing beam travels at about 2×10^6 cm/sec, and the wings travel at 5×10^5 cm/sec.

The features noted above are quite reproducible from shot to shot. However, the plasma flow is dependant on the laser energy and pulse shape. Fig. 3 shows shadowgraphs taken with the laser in the low-energy, short pulse mode. As can be seen, the prominent wings are absent; the fast beam and slow triangular component are still visible, however. Langmuir probe measurements confirm this description of the flow pattern.

Also visible in these photographs, in the slow plasma component near the rod, is a network of striations. These striations are evidently caused by the traditional shadowgraph effects[7] of second derivatives $\partial^2\eta/\partial z^2$. These refraction effects indicate the presence of strong density fluctuations in the slow plasma component.

This interpretation is confirmed by the schlieren photographs shown in Fig. 4. For these shots, a horizontal knife edge was used, so that vertical density gradients become visible. The bright streaks in these pictures correspond to the striations in the shadowgraphs, and verify the presence of small-scale irregularities in the magnetized plasma.

IV. DISCUSSION

Some of the features noted in the photographs are understandable in light of previous work, while others are rather unexpected. The appearance

of a narrow, collimated beam in magnetized laser-plasma flows has been noted by a number of workers.[8-10] The effect is explained by the electric polarization of the plasma and subsequent $\vec{E} \times \vec{B}$ drift across the magnetic field.[11-12] Since magnetic probes have indicated that our plasma perturbs the B-field by only 10% at radii > 4 cm, the plasma is permeated by the field, and polarization is expected. Indeed, we have measured vertical E-fields of the appropriate magnitude $E = \frac{vB}{c} \approx 7 \times 10^{-2}$ statvolt/cm. It therefore appears that the traditional concept of polarization drift across the field is applicable to our experiment.

The appearance of the narrow, forward-pointing beam is presumably due to the initial preferential expansion of the plasma normal to the target face. The "wings" visible in the long-pulse mode shadowgraphs, however, are unexplained at this time. They may result from the extra laser energy available in this mode. The longer duration of the laser pulse may also be important, since the "tail" of the pulse can be partially absorbed by the emerging plasma. The resulting higher electron temperature, might then change the flow dynamics by some presently unknown process.

Finally, we consider the refractive effects seen in the shadowgraph and schlieren pictures. The formation of a distinct boundary at the plasma edge is obvious, as are a number of "ripples" inside the plasma. The thickness of these striations is less than 2mm. These features are only visible in the slow plasma component near the target.

The most plausible interpretation of these sharp gradients is that they are some sort of shock wave or soliton. It would be interesting to know whether they are collisionless. To decide this matter, we must calculate the multi-Coulomb mean free path for ion-ion collisions[13]

reek capital "lambda"

$$L = [8\pi n_i \left(\frac{e^2}{m_i v^2}\right) \ln \Lambda]^{-1}, \tag{1}$$

where ln Λ is the Coulomb logarithm and v is the velocity of the shock relative to the plasma. A collisional shock would travel at a velocity $v = (k\ T_i/m_i)^{1/2}$, where T_i is the temperature. If T_i = 5eV, we get $v = 2 \times 10^5$ cm/sec. Using this velocity and the estimated density $n_i \approx 5 \times 10^{14}/\text{cm}^3$ in eq. (1), we calculate the mean free path $L \approx 0.1$ mm. Since this is smaller than the observed striations, a collisional shock is a plausible model for the effect. Such a series of shock waves could be excited by the supersonic impact of the plasma against the "magnetic

reek beta"

barrier" at $\beta = 8\pi\ n_i m_i U^2/B^2 = 1$, where U is plasma flow velocity. Since the $\beta = 1$ point occurs several cm from the target, and this is where the striations appear, the model appears consistent.

Because of the sensitivity of the resonant optical techniques used in this study, several new and unexpected features of magnetized plasma flow have been uncovered. Further research along these lines may reveal other interesting aspects of plasma dynamics.

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This research was initiated and guided by the late D.W. Koopman; the memory of his dedication and perseverence has been a constant inspiration to the authors. We are also grateful to T.J. McIlrath for discussions and guidance.

This report is from a dissertation to be submitted to the Graduate School, University of Maryland, by Gerard P. Jellison in partial fulfillment of the requirements for the Ph.D. degree in Physics.

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LIST OF FIGURES

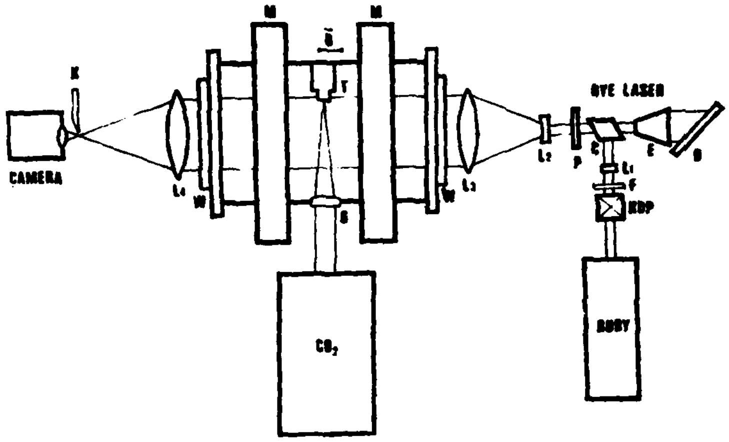
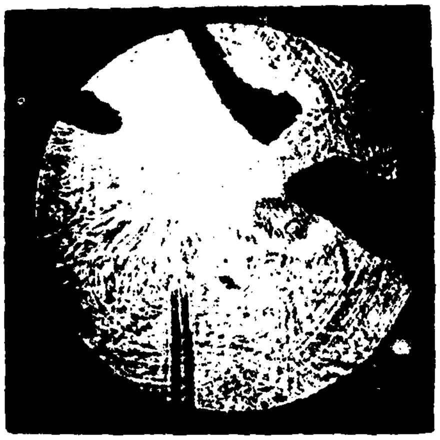
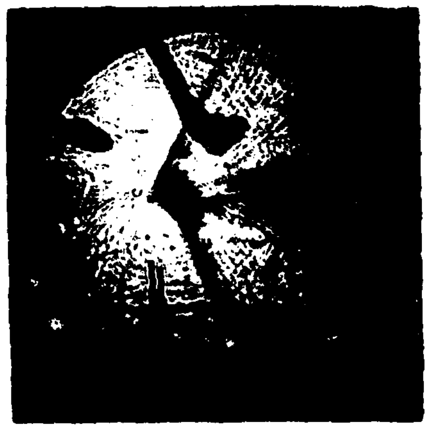


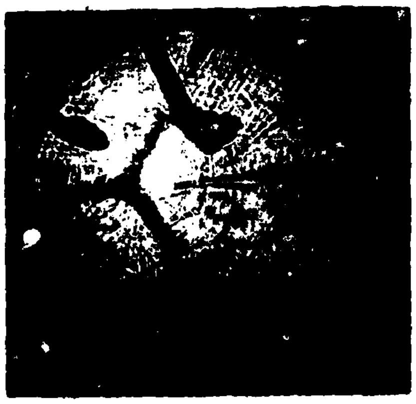
Figure 1



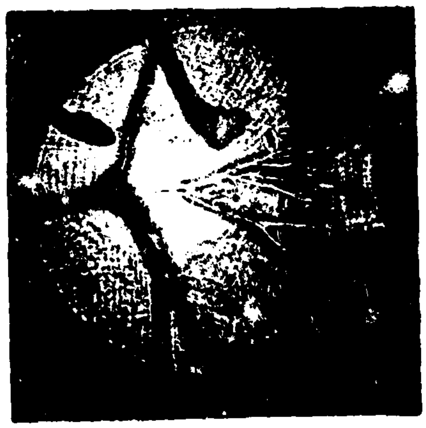
4 µ SEC



6 µ SEC

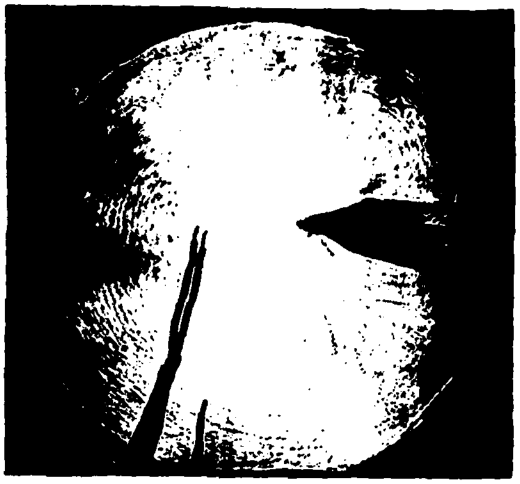


8 µ SEC

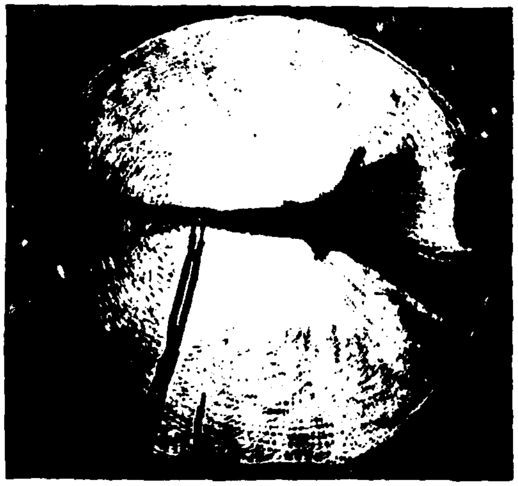


10 µ SEC

Fig 2



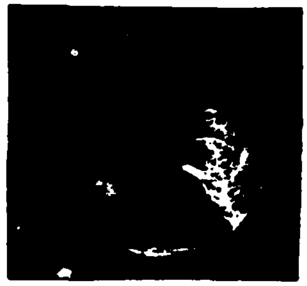
5 μ SEC 1.7 KG



9 μ SEC 1.7 KG

Fig ?

5 μSEC



6 μSEC

8 μSEC

9 μSEC

Fig 4

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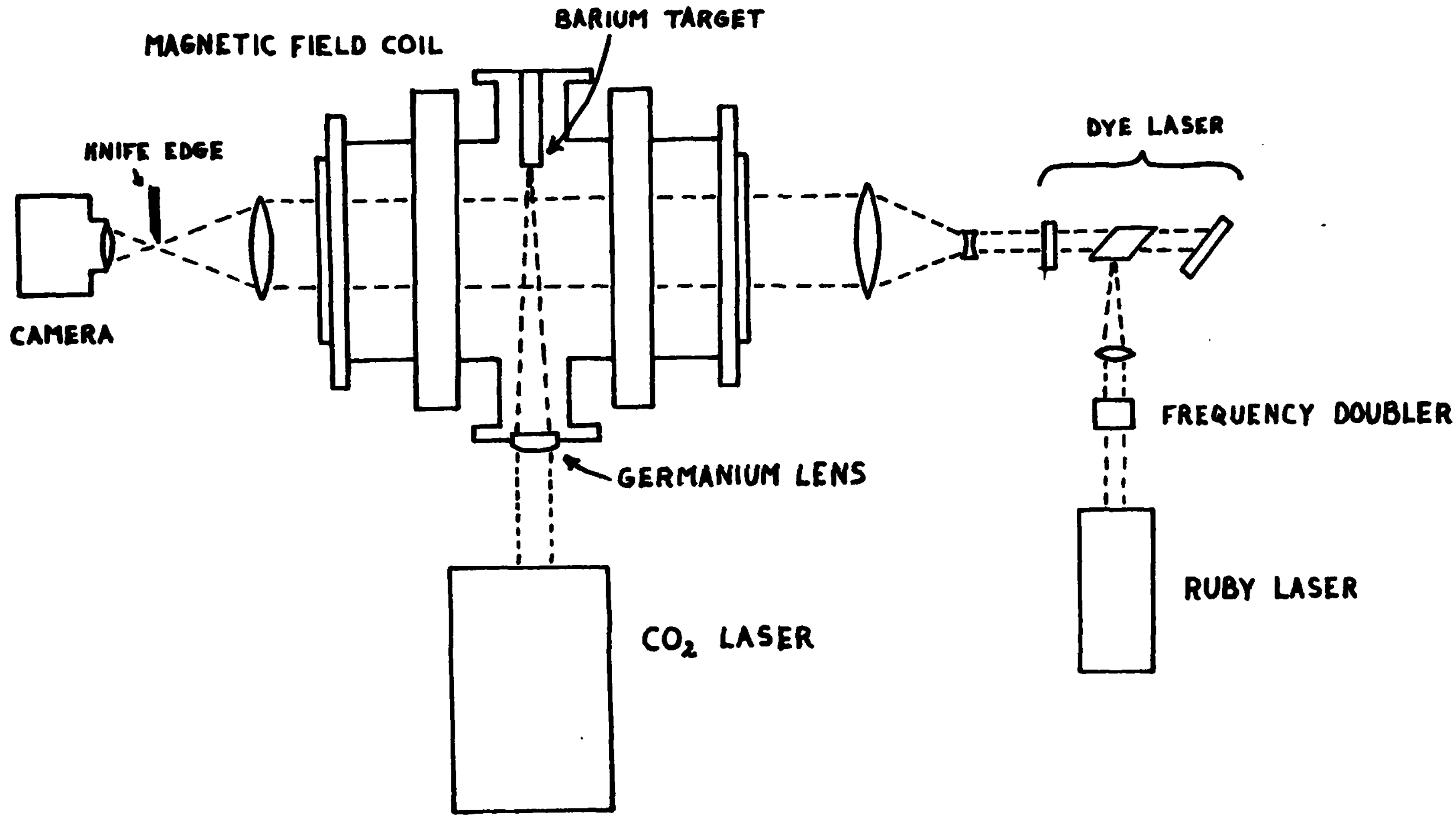

Figure 1. Experimental setup (shown in schlierne configuration).

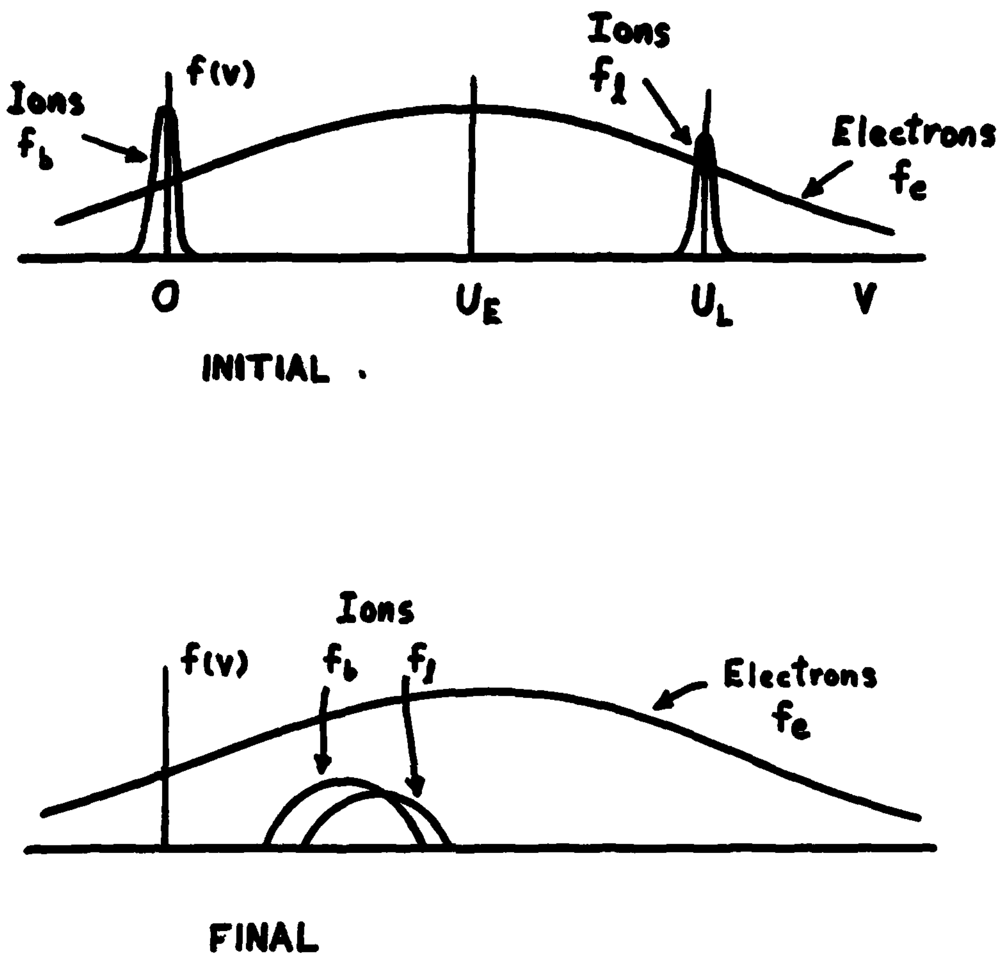

Figure 2. Typical distribution functions for a flowing laser-produced plasma (subscript ℓ) expanding into a stationary background plasma (subscript b). If the initial conditions (top) are unstable, plasma turbulence leads to redistribution of ion velocity (bottom).

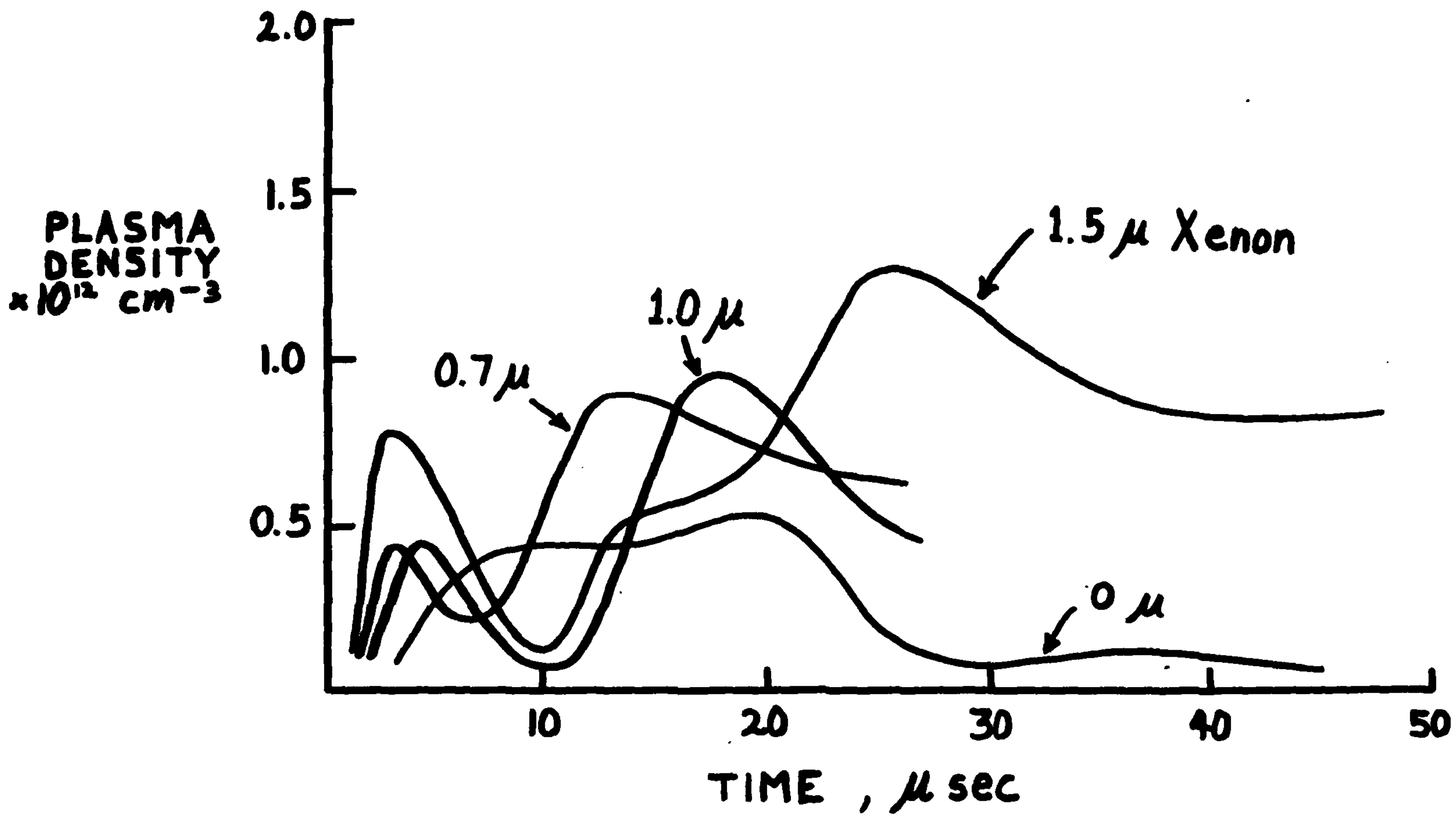

Figure 3. Barium plasma density derived from resonant scattering vs time for several values of xenon background pressure. Magnetic field stregnth is 1.7kG.

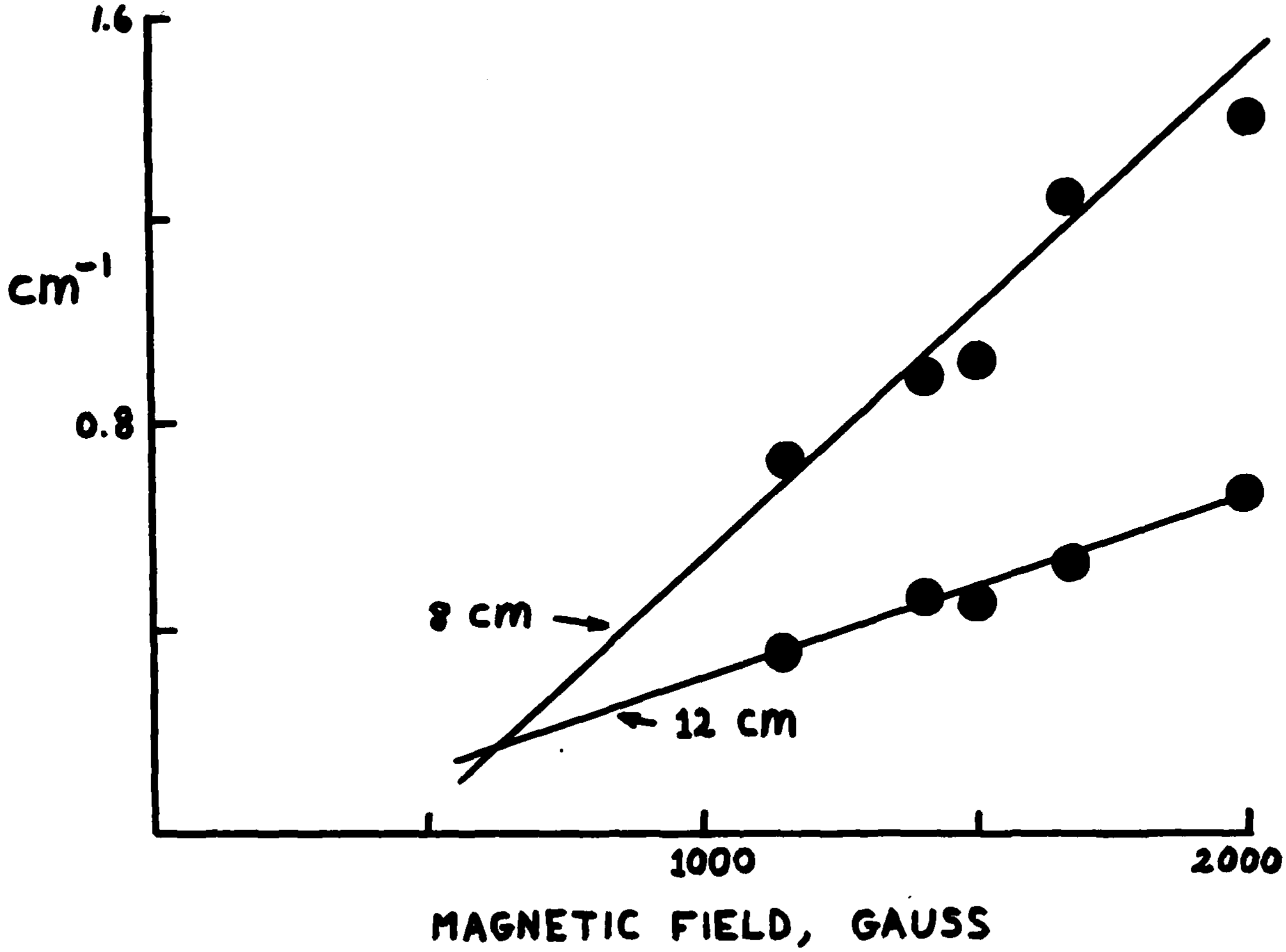

Figure 4. Reciprocal of the half-thickness of the plasma front vs. magnetic field strength, with 1.0μ xenon background.

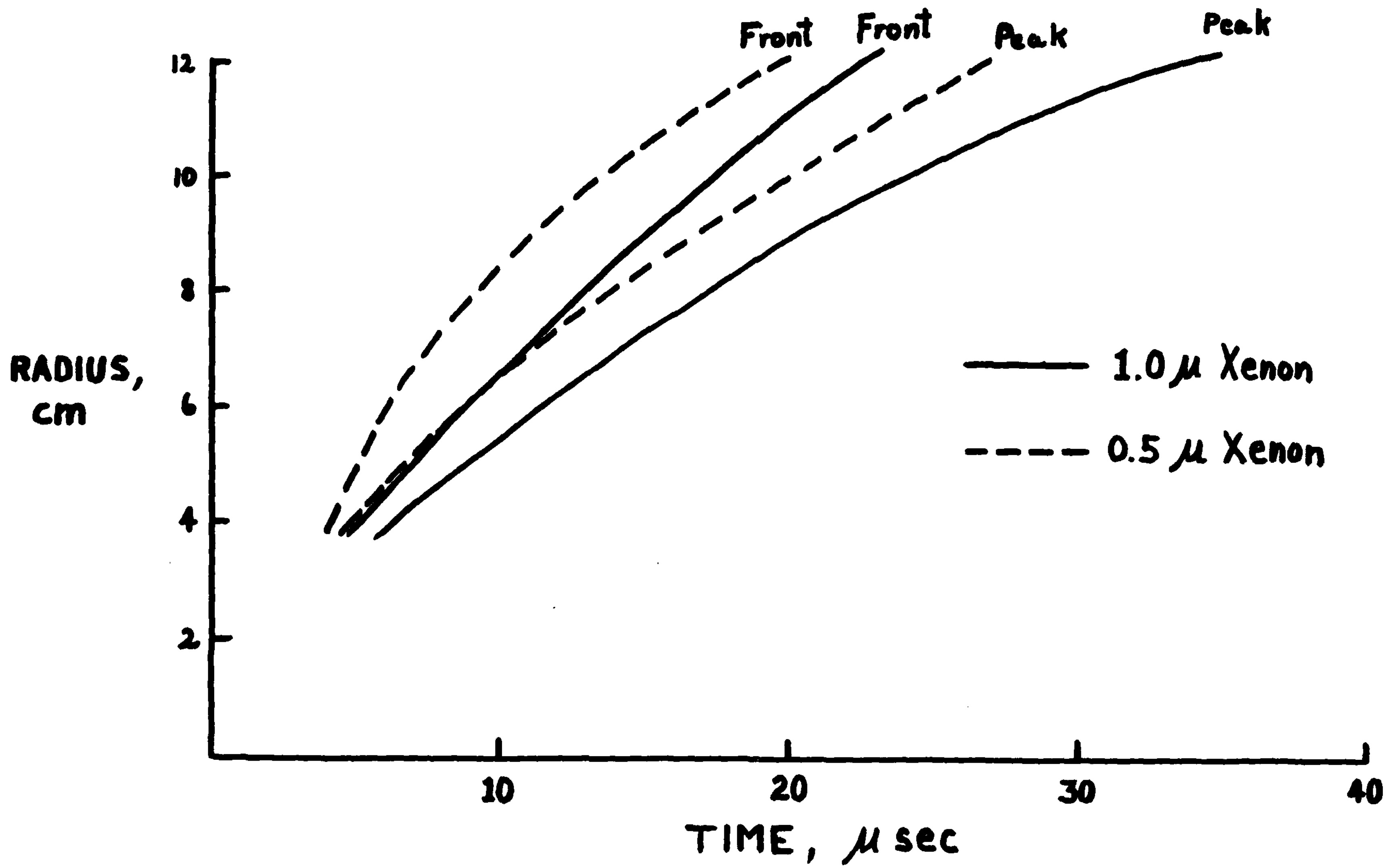

Figure 5. Position vs. time of the flowing barium plasma front and peak into two different xenon background pressures. Magnetic field strength is 1.8kG.

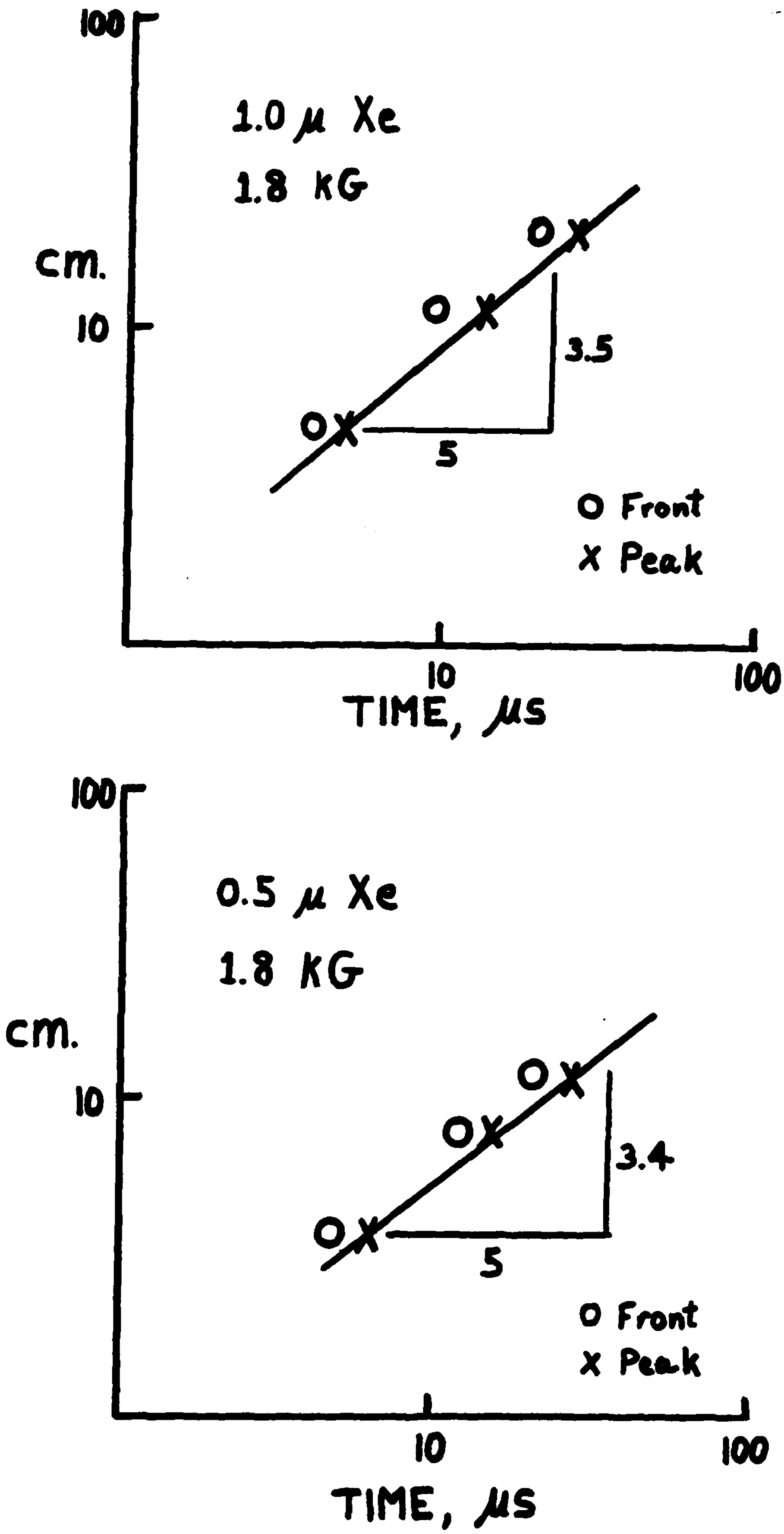

Figure 6. Distance v-. time for the flowing barium plasma into two different xenon background pressures. Magnetic field is 1.8kG.

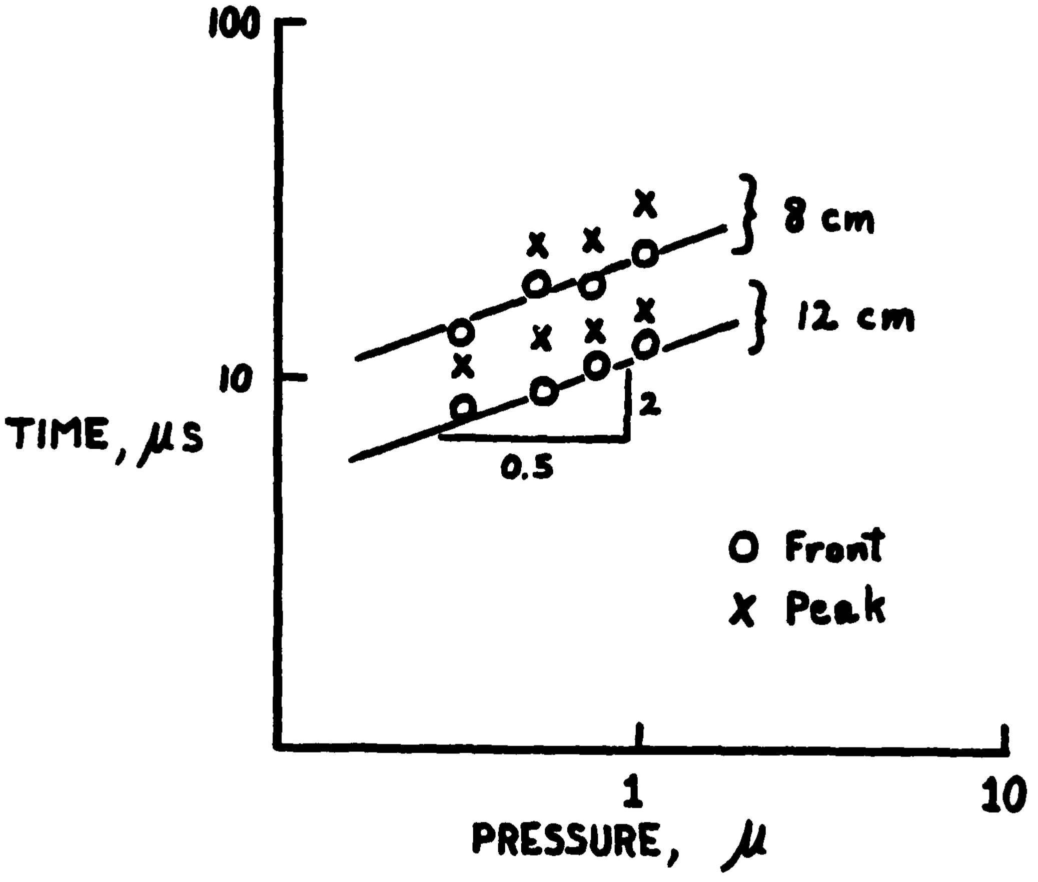

Figure 7. Time vs. xenon background pressure for the flowing barium plasma at two distances from the target.